Simplifying Complex Problems with Systems Engineering Tools: A Lunar Architecture Analysis Case Study

Thomas K. Percy

Science Applications International Corporation
Huntsville, AL

The analysis of lunar mission architectures is a complex problem dealing with many different propulsive elements and payloads moving through a series of locations to deliver humans and cargo to the moon. While the general systems engineering process is largely tied to the development of an end product, many of the tools commonly employed by systems engineers can be used to simplify these complex and abstract mission analyses. These tools can help the annalist gain a better overall understanding of the problem, its trends and possible solutions by better defining element interactions and functions. Sensitivity studies that employ trade tree analysis can give the engineer insight into performance trends and the benefits and penalties associated with certain design decisions. Finally, these tools can be implemented to help define the structure of simple, zero-level, Excel-based analysis tools that can assess broad, expansive trade spaces allowing mission planners to begin to formulate informed perceptions of mission performance trends. In this paper, the application of these system engineering tools and methodologies to the analysis of lunar mission architectures is discussed as well as some of the results of those analyses.

1.0 Introduction

As part of the Vision for Exploration, major tasks have been undertaken both within and out side of NASA to begin to understand the requirements that exist to return humans to the lunar surface. The complexity of this problem is, at many times, daunting and requires some simplification in order to begin to isolate the major underlying trends and performance drivers. Some systems engineering tools and methodologies lend themselves well to this task and have been employed in various lunar exploration architecture analysis projects currently underway. The following pages outline how these systems engineering tools are being used and examples of some analyses and results will be shown. All of the work referred to in this paper was completed under the Space Transportation Programs & Projects Office at the Marshall Space Flight Center in Huntsville, Alabama.

1.1. Systems Engineering

The general systems engineering process is mostly geared towards the end goal of developing a product. The process works through phases of concept definition, requirements definition, design, testing and production. Many tools and methodologies are employed throughout this process to define and track the use of requirements, perform analyses that will lead to an optimal product, and follow the development and deployment of that product to the end customer. Systems and sub-systems are designed and tracked throughout the process to ensure proper operation and integration is achievable. While this process may be well suited for the development of actual, tangible products, the application of the process to abstract or highly conceptual problems is much less straight forward. For these problems, where the tangible product or answer may be years or even decades from definition, a useful subset of the systems engineering process and tool set may be of greater use to the analyst than the process as a whole.

1.2. Lunar Architecture Analysis: A Complex Problem

One such problem is the analysis of lunar exploration architectures. This problem, involving many systems and many functions, presents an extremely broad trade space of possible solutions. Each solution may have its own merits and drawbacks, however before detailed mission and systems design work can begin, this trade space must be trimmed to allow only those most promising of answers to be further considered. This requires a quick analysis process that identifies the general trends and sensitivities inherent in this mission.

From a zero-level perspective of the analysis of this problem, the complexity of the lunar exploration architecture lies in the number of possible combinations of payloads, propulsive elements, mission modes and staging orbits. Additionally of interest at a high level is the selection of propellants and stage performance parameters for each propulsive element identified. In order to cull the trade space and begin to select modes for detailed analyses, the interdependencies of these mission and systems characteristics must be identified and understood.

There are several options for each of these characteristics that are currently under consideration by those analyzing the lunar exploration architectures. Payloads for this mission will typically be required to support the human crew for a specified number of days. The mass of these elements and the splitting of their functions vary greatly from case to case. The general mission mode (for example, Lunar Orbit Rendezvous or Lunar Direct Return) plays a large role in defining the maneuvers required in a given mission and which stages will perform those maneuvers.

Although a general set of propulsive maneuvers has been identified (including trans-lunar injection, lunar orbit insertion, trans-Earth injection, lunar descent and lunar ascent burns), the stages used to perform these burns may vary between mission options. Some stages may be required to perform more than one burn and some burns may be split among more than one stage. The selection of staging locations (including Earth-Moon L1 and circular and elliptical lunar parking orbits) will drive the delta-v requirements of those burns. Additionally, the performance of the stages, including the selection of propellants, will drive the overall mission performance greatly. The interdependencies between these major characteristics further complicate the problem.

While the overall systems engineering process does not lend itself well to these broad, conceptual analyses, certain tools and methods within that process prove to be quite useful. Functional decomposition of the system interactions within the problem help to quickly identify major interdependencies between mission elements. Trade tree development, typically used to organize the trades of major product characteristics in an attempt to isolate the most effective end product in the systems engineering process, can be used to provide structure and organization to the often remarkably broad trade spaces inherent in these analyses. These tools, along with simple systems models, can provide the engineer with the necessary understanding to develop informed recommendations for further detailed study.

2.0 Systems Engineering Tools and Methods

2.1. N^2 Diagrams: Functional Decomposition

The N^2 diagram is a tool typically used in systems engineering to track the interdependencies of various functions within a system or sub-system. The tool can also provide interface management between sub-systems. In application to lunar architecture analyses, this tool is useful not only for managing the interfaces of the various propulsive stages but also for mapping the calculation technique for sizing these stages.

An example of an N^2 diagram as it applies to an individual stage sizing calculation can be seen in Figure 1. Here, the various functions of the stage are represented along the diagonal. In the upper right sector of the diagram are the various elements being fed into the calculations for other functions. Those elements being fed back into previous calculations are found in the lower left sector. The process of feed forward and feed back creates an iterative calculation that will eventually converge on a solution.

In the stage calculation, the first required function of the stage is to move payload through space. The

Move Payload Through Space	Delta-V & Payload Mass	
	Provide Energy for Velocity Change	Propellant Load
	Dry Mass	**Support Propellant & Structure**

Figure 1. N^2 Diagram for Individual Stage Calculation

beginning and end locations and the time to perform the maneuver are defined for this function and the delta-v requirement and mass of the payload are fed forward to the second function. This second stage function is to provide energy to accommodate the required delta-v. The calculation surrounding this function uses the inputs from the previous function to calculate a propellant load. To simplify the calculations, propellant mass fractions are assumed for each stage. These mass fractions are functions that scale with propellant load and provide a reasonably accurate stage dry mass calculation for the purposes of high level assessments. This dry mass calculation covers the third function of the stage which is to support the propellant and other loads experienced by the stage. Once a dry mass is calculated it is fed back into the propellant calculation to provide a new initial mass for the burn and this iteration continues until a total stage mass is calculated.

Similar to the stage calculation, N^2 diagrams can be constructed to represent entire mission architectures. Each burn is represented as a function performed by stages and displayed along the diagonal. Each of these functions is represented by a nested N^2 diagram for the stage that performs the burn. Figure 2 shows an N^2 diagram for a lunar orbit rendezvous mission along with an example of the nested stage N^2 diagram for the trans-Earth injection stage.

In Figure 2, the six separate burns that make up a lunar orbit rendezvous mission are represented. The

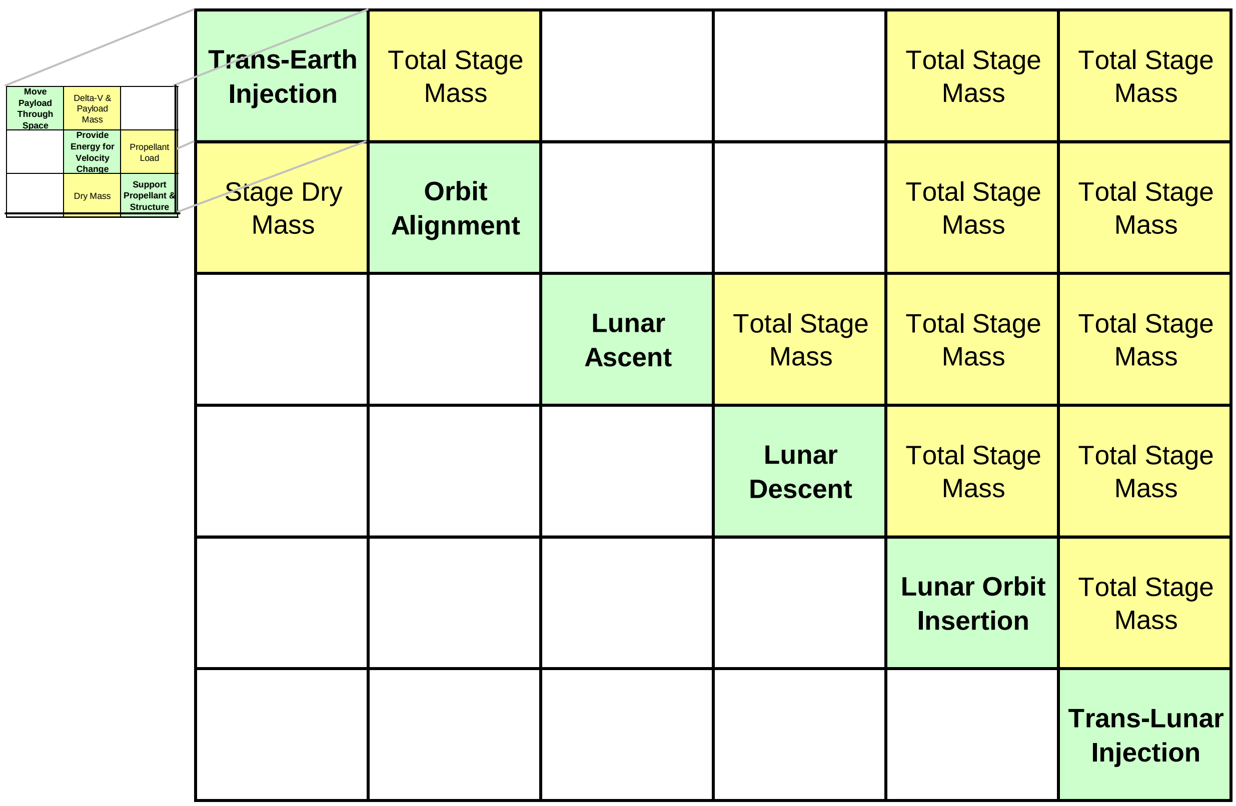

Figure 2. N^2 Diagram for a Lunar Orbit Rendezvous Mission

elements that are fed forward in this case are the total stage masses. The analysis begins with the final stage in the series and works its way back to the first. Each stage mass that is fed forward becomes a payload for the next stage in the analysis. Thus, according to the diagram, each stage in the mission is payload for the trans-lunar injection (TLI) stage.

In the case of the orbit alignment burn and the trans-Earth injection burn, they are performed with the same stage. The trans-Earth injection (TEI) stage is payload for the orbit alignment stage however, the dry mass required for the orbit alignment burn must be accounted for in the TEI stage calculation. Therefore, an iterative calculation exists much like the propellant mass – dry mass iteration in the stage mass calculation, with the orbit alignment stage dry mass being fed back into the TEI stage calculation.

This N^2 diagram, along with a delta-v table, allows the analyst to quickly determine which stages are potential mission performance drivers.

Variations on the lunar orbit rendezvous mission mode include combining burns. One such example is the TEI - orbit alignment burn calculation previously mentioned. Another example of this can be seen in Figure 3, where the mission represented uses the trans-lunar injection (TLI) stage to perform the lunar orbit insertion (LOI) burn. Again, as with the TEI – orbit alignment combination, the dry mass of the TLI stage must be fed back into the LOI burn calculation. This variation on the lunar orbit rendezvous mission mode can be costly given that the TLI stage is typically the largest stage and adds unnecessary mass to an already heavy lunar orbit insertion payload (the number of stages the LOI stage carries through its burn is second only to the TLI stage). However, in some propellant trades where the TLI stage vastly outperforms the propellant of choice for the alternative stand-alone LOI stage, there may be an advantage to using the higher performing stage. This shows that, while N^2 diagrams can help put the pieces together, they do not always provide the full picture. For that, trade studies are usually necessary.

Trans-Earth Injection	Total Stage Mass			Total Stage Mass	Total Stage Mass
Stage Dry Mass	**Orbit Alignment**			Total Stage Mass	Total Stage Mass
		Lunar Ascent	Total Stage Mass	Total Stage Mass	Total Stage Mass
			Lunar Descent	Total Stage Mass	Total Stage Mass
				Lunar Orbit Insertion	Total Stage Mass
				Stage Dry Mass	**Trans-Lunar Injection**

Figure 3. N^2 Diagram for LOR with Combined TLI - LOI

In Figure 4 an N^2 diagram is displayed for a lunar direct return mission. In this case the same stage is used for descent, ascent and TEI. This creates several inter-stage iterative calculations to determine the total mass of that stage. With one stage performing a significant portion of the total mission it could be assumed that this stage will be a mission performance driver. As will be seen in the mission analysis examples, this is so true that it is always advantageous to split the system into a descent stage and an ascent – TEI stage for vastly improved mission performance.

Trans-Earth Injection		Total Stage Mass	Total Stage Mass	Total Stage Mass	Total Stage Mass
	Orbit Alignment				
Stage Dry Mass		**Lunar Ascent**	Total Stage Mass	Total Stage Mass	Total Stage Mass
Stage Dry Mass		Stage Dry Mass	**Lunar Descent**	Total Stage Mass	Total Stage Mass
				Lunar Orbit Insertion	Total Stage Mass
				Stage Dry Mass	**Trans-Lunar Injection**

Figure 4. N^2 Diagram for a Lunar Direct Return Mission

2.2. Trade Trees: Trade Analysis Organization

While the N^2 diagram is a useful tool for determining element interdependencies, the true affects of those interdependencies are not usually readily apparent. To develop a general understanding of the mission performance and the tendencies of the trade space, trade and sensitivity analyses are typically performed. In the general systems engineering process, these analyses are used to trade the characteristics of a product in order to find the best balance between all characteristics in an attempt to develop the most optimal product possible. In much the same way, the trade and sensitivity analyses of these complex mission problems can help identify, at a high level, the decisions that may be more or less favorable. Once these have been isolated, more detailed analysis can be performed to determine which combination of mission modes and element functions will yield the most optimal overall mission architecture.

For the analysis of these types of missions, where so many variables and possible trades exist and appear to be so tightly interconnected, the task of laying out a complete mapping of the trade space may seem difficult. With the help of trade trees, the nebulous trade space begins to take shape. At each decision point, branches exist that represent the different paths that can be taken in the decision making process. These branches extend until all possible decision points have been included. Therefore, one complete branch of the trade tree represents a unique combination of decisions that leads to a unique architecture for completing the mission.

Sensitivity analyses can be mapped in much the same way. For example, a common sensitivity to study in these problems is the sensitivity to variations in specific impulse. Once a propellant is selected, a nominal specific impulse is assumed. However, with many of the systems under consideration, significant variations can exist with respect to what that nominal specific impulse is. In the case of a methane engine, since one has not been built and very few have been designed, the specific impulse of that system could vary from 350 seconds to 390 seconds depending on which source is used to gather data for the analysis. It is, therefore, useful to know the system's performance variations with respect to specific impulse variations in order to determine whether or not the system can still successfully perform the mission across the range of values. By constructing a trade tree where the decision points are the values for specific impulse, a sensitivity study can be easily mapped.

While this sensitivity study mapping may not, by itself, be entirely useful, the combination of trade and sensitivity maps can create a complete trade tree for a significant analysis. An example of such a trade tree can be viewed in Figure 5. Notice, since the sensitivity and trade analyses have been combined, this trade tree is very large. This tree starts with the selection of the lunar direct return mission mode and proceeds to the decision of whether or not to pre-deploy surface assets. From there it deals with staging or not staging the lander and sensitivities to the selection of propellant and variation of specific impulse of those lander elements. The first branch of the trade tree can be seen in Figure 6.

At this scale of trade tree, in order to truly be useful as an analysis tool, the tree must be coupled with a simple modeling capability that can quickly assess these traded options. This modeling capability, discussed in the following section, is based in Excel. As such, a translation from the typical trade tree form shown in Figure 5a to a form usable by Excel must also be made. The Excel version of the trade tree can be seen in Figure 5b. A discussion of how it is used can be found in the following section.

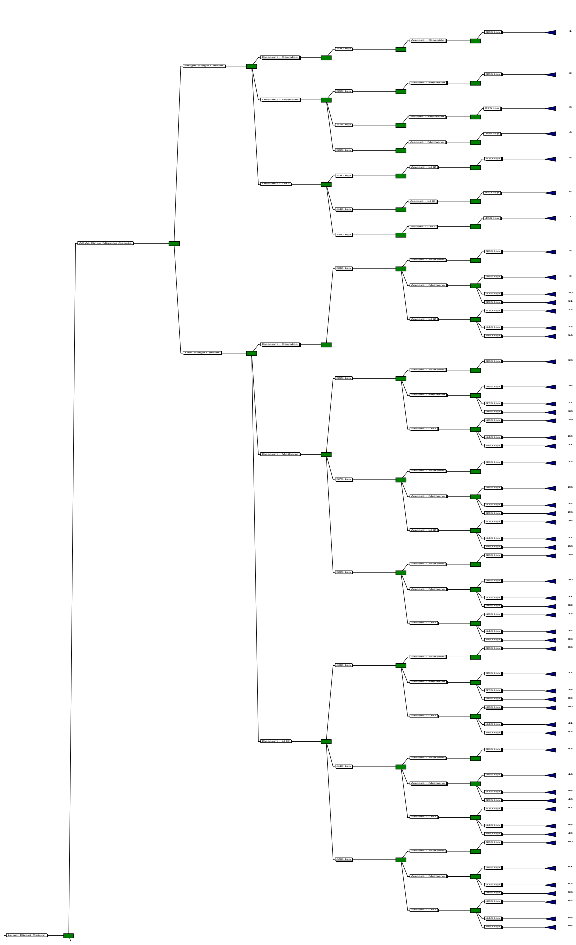

Figure 5a. The Traditional Trade Tree

All-At-Once	Single Stage Lander	Descent Storable	330 ISP	Ascent Storable	330 ISP
All-At-Once	Single Stage Lander	Descent Methane	355 ISP	Ascent Methane	355 ISP
All-At-Once	Single Stage Lander	Descent Methane	375 ISP	Ascent Methane	375 ISP
All-At-Once	Single Stage Lander	Descent Methane	395 ISP	Ascent Methane	395 ISP
All-At-Once	Single Stage Lander	Descent LH2	430 ISP	Ascent LH2	430 ISP
All-At-Once	Single Stage Lander	Descent LH2	440 ISP	Ascent LH2	440 ISP
All-At-Once	Single Stage Lander	Descent LH2	450 ISP	Ascent LH2	450 ISP
All-At-Once	Two Stage Lander	Descent Storable	330 ISP	Ascent Storable	330 ISP
All-At-Once	Two Stage Lander	Descent Storable	330 ISP	Ascent Methane	355 ISP
All-At-Once	Two Stage Lander	Descent Storable	330 ISP	Ascent Methane	375 ISP
All-At-Once	Two Stage Lander	Descent Storable	330 ISP	Ascent Methane	395 ISP
All-At-Once	Two Stage Lander	Descent Storable	330 ISP	Ascent LH2	430 ISP
All-At-Once	Two Stage Lander	Descent Storable	330 ISP	Ascent LH2	440 ISP
All-At-Once	Two Stage Lander	Descent Storable	330 ISP	Ascent LH2	450 ISP
All-At-Once	Two Stage Lander	Descent Methane	355 ISP	Ascent Storable	330 ISP
All-At-Once	Two Stage Lander	Descent Methane	355 ISP	Ascent Methane	355 ISP
All-At-Once	Two Stage Lander	Descent Methane	355 ISP	Ascent Methane	375 ISP
All-At-Once	Two Stage Lander	Descent Methane	355 ISP	Ascent Methane	395 ISP
All-At-Once	Two Stage Lander	Descent Methane	355 ISP	Ascent LH2	430 ISP
All-At-Once	Two Stage Lander	Descent Methane	355 ISP	Ascent LH2	440 ISP
All-At-Once	Two Stage Lander	Descent Methane	355 ISP	Ascent LH2	450 ISP
All-At-Once	Two Stage Lander	Descent Methane	375 ISP	Ascent Storable	330 ISP
All-At-Once	Two Stage Lander	Descent Methane	375 ISP	Ascent Methane	355 ISP
All-At-Once	Two Stage Lander	Descent Methane	375 ISP	Ascent Methane	375 ISP
All-At-Once	Two Stage Lander	Descent Methane	375 ISP	Ascent Methane	395 ISP
All-At-Once	Two Stage Lander	Descent Methane	375 ISP	Ascent LH2	430 ISP
All-At-Once	Two Stage Lander	Descent Methane	375 ISP	Ascent LH2	440 ISP
All-At-Once	Two Stage Lander	Descent Methane	375 ISP	Ascent LH2	450 ISP
All-At-Once	Two Stage Lander	Descent Methane	395 ISP	Ascent Storable	330 ISP
All-At-Once	Two Stage Lander	Descent Methane	395 ISP	Ascent Methane	355 ISP
All-At-Once	Two Stage Lander	Descent Methane	395 ISP	Ascent Methane	375 ISP
All-At-Once	Two Stage Lander	Descent Methane	395 ISP	Ascent Methane	395 ISP
All-At-Once	Two Stage Lander	Descent Methane	395 ISP	Ascent LH2	430 ISP
All-At-Once	Two Stage Lander	Descent Methane	395 ISP	Ascent LH2	440 ISP
All-At-Once	Two Stage Lander	Descent Methane	395 ISP	Ascent LH2	450 ISP
All-At-Once	Two Stage Lander	Descent LH2	430 ISP	Ascent Storable	330 ISP
All-At-Once	Two Stage Lander	Descent LH2	430 ISP	Ascent Methane	355 ISP
All-At-Once	Two Stage Lander	Descent LH2	430 ISP	Ascent Methane	375 ISP
All-At-Once	Two Stage Lander	Descent LH2	430 ISP	Ascent Methane	395 ISP
All-At-Once	Two Stage Lander	Descent LH2	430 ISP	Ascent LH2	430 ISP
All-At-Once	Two Stage Lander	Descent LH2	430 ISP	Ascent LH2	440 ISP
All-At-Once	Two Stage Lander	Descent LH2	430 ISP	Ascent LH2	450 ISP
All-At-Once	Two Stage Lander	Descent LH2	440 ISP	Ascent Storable	330 ISP
All-At-Once	Two Stage Lander	Descent LH2	440 ISP	Ascent Methane	355 ISP
All-At-Once	Two Stage Lander	Descent LH2	440 ISP	Ascent Methane	375 ISP
All-At-Once	Two Stage Lander	Descent LH2	440 ISP	Ascent Methane	395 ISP
All-At-Once	Two Stage Lander	Descent LH2	440 ISP	Ascent LH2	430 ISP
All-At-Once	Two Stage Lander	Descent LH2	440 ISP	Ascent LH2	440 ISP
All-At-Once	Two Stage Lander	Descent LH2	440 ISP	Ascent LH2	450 ISP
All-At-Once	Two Stage Lander	Descent LH2	450 ISP	Ascent Storable	330 ISP
All-At-Once	Two Stage Lander	Descent LH2	450 ISP	Ascent Methane	355 ISP
All-At-Once	Two Stage Lander	Descent LH2	450 ISP	Ascent Methane	375 ISP
All-At-Once	Two Stage Lander	Descent LH2	450 ISP	Ascent Methane	395 ISP
All-At-Once	Two Stage Lander	Descent LH2	450 ISP	Ascent LH2	430 ISP
All-At-Once	Two Stage Lander	Descent LH2	450 ISP	Ascent LH2	440 ISP
All-At-Once	Two Stage Lander	Descent LH2	450 ISP	Ascent LH2	450 ISP

Figure 5b. The Excel Trade Tree

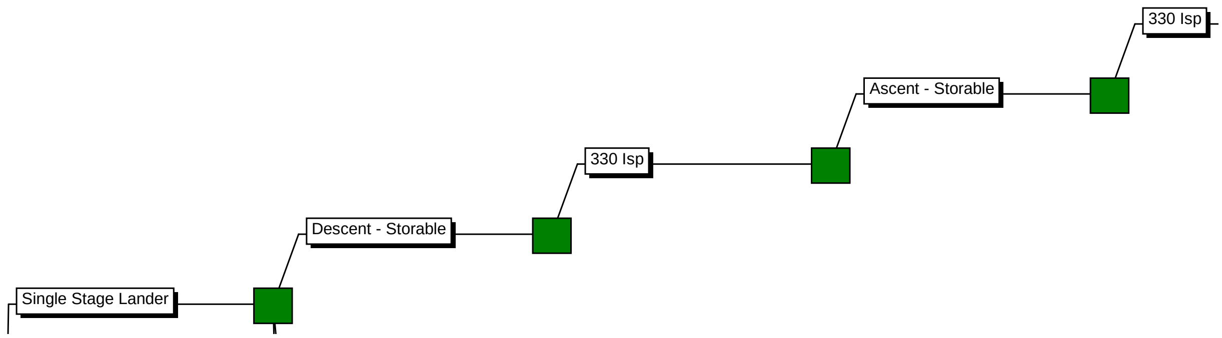

Figure 6. A Single Trade Tree Branch

2.3. Simplified Modeling: Mass fraction-based assessment

With the interdependencies identified and the trade space mapped, attention then turns to a method for quickly analyzing the trade space while producing reasonably accurate results that can aid in drawing some conclusions about the behavior of the mission performance parameters. For this purpose, an Excel-based stage mass calculation is used. This calculation relies on propellant mass fractions to size the stage dry mass. To ensure some level of accuracy, relationships were developed between propellant mass fraction and propellant load. Also ensuring some level of accuracy is a propellant boil-off calculation routine that approximates the amount of propellant lost due to prolonged exposure to the space environment. Delta-v requirements are supplied by outside mission analyses.

In order to make use of the Excel-based trade trees, Visual Basic code is constructed. This code calls values from a singe trade tree branch into the mass modeling routine. With the stage mass calculators arranged to reflect the stage interdependencies identified in the N^2 diagrams, these trade tree values are inserted into the model and an entire mission can be modeled based on the characteristics of that single branch. The code then reports the relevant data from that run and proceeds to call the next branch of the trade tree. In a matter of minutes, a trade tree of over 250 branches can be assessed and the data provided to the engineers to begin assessing the trends and sensitivities of the mission architecture. In the next section of the paper, several examples of this process are discussed along with some sample results and conclusions that were determined using this analysis process.

3.0 Analysis Case Studies: Methods & Results

Several case studies will now be presented to exemplify the process that has been previously discussed. In the continued support of NASA’s Vision for Exploration, a series of quick studies are being performed on segments of the overall lunar mission architecture trade space to help better define the trends and sensitivities that exist and begin to isolate those specific architectures that offer the most promise of actually returning humans to the surface of the moon. Three such quick studies are presented here.

The first involves the lunar direct return mission mode and investigates the trade of staging versus not staging the lunar lander and the sensitivity to specific impulse variations of the descent and ascent stages. The second case trades the parking orbit of a lunar orbit rendezvous mission mode between circular and elliptical. In this case, all possible stage-propellant combinations were assessed in both parking orbits to generate a complete picture of the trade. Finally, a trade study of propellant choice for each propulsive stage is presented for the lunar orbit rendezvous mission mode. This study begins to isolate mission sensitivity to the selection of propellants for each stage.

3.1. Lunar Direct Return Mode: Trades & Sensitivities

In the lunar direct return mission mode, the crew is sent to the moon in a single habitat. This habitat is carried to the surface where it provides a work environment and life support for the crew during their seven day stay on the lunar surface. The crew and habitat are lifted off the surface of the moon and returned directly to Earth by a single stage. This mission involves carrying a significant payload through some of the most delta-v intensive maneuvers (lunar descent and ascent) and relies heavily on high stage performance.

For the purposes of this particular analysis, a crew habitat mass of 11 MT was assumes. It was further assumed that the Earth departure stage (EDS) would only use Lox/LH_2 as its propellant, due to its high payload and delta-v requirement. A single stage lunar surface access module (LSAM) was traded against a two stage LSAM where one stage would perform descent and another would perform ascent and trans-Earth injection. Also assessed was the sensitivity of the architecture to variations in propellant choice for those stages. This assessment included Lox/LH_2, Lox/CH_4 and NTO/N_2H_4. In total, 56 possible combinations existed for the analysis. The trade tree and N^2 diagram for this analysis are displayed in Figure 7.

Staging	Descent Isp	Ascent Isp
No	330	330
No	355	355
No	375	375
No	395	395
No	430	430
No	440	440
No	450	450
Yes	330	330
Yes	330	355
Yes	330	375
Yes	330	395
Yes	330	430
Yes	330	440
Yes	330	450
Yes	355	330
Yes	355	355
Yes	355	375
Yes	355	395
Yes	355	430
Yes	355	440
Yes	355	450
Yes	375	330
Yes	375	355
Yes	375	375
Yes	375	395
Yes	375	430
Yes	375	440
Yes	375	450
Yes	395	330
Yes	395	355
Yes	395	375
Yes	395	395
Yes	395	430
Yes	395	440
Yes	395	450
Yes	430	330
Yes	430	355
Yes	430	375
Yes	430	395
Yes	430	430
Yes	430	440
Yes	430	450
Yes	440	330
Yes	440	355
Yes	440	375
Yes	440	395
Yes	440	430
Yes	440	440
Yes	440	450
Yes	450	330
Yes	450	355
Yes	450	375
Yes	450	395
Yes	450	430
Yes	450	440
Yes	450	450

Trans-Earth Injection		Total Stage Mass	Total Stage Mass	Total Stage Mass	Total Stage Mass
	Orbit Alignment				
Stage Dry Mass		**Lunar Ascent**	Total Stage Mass	Total Stage Mass	Total Stage Mass
Stage Dry Mass		Stage Dry Mass	**Lunar Descent**	Total Stage Mass	Total Stage Mass
				Lunar Orbit Insertion	Total Stage Mass
				Stage Dry Mass	**Trans-Lunar Injection**

Figure 7. Lunar Direct Return N^2 and Trade Tree

The results of these analyses support several general conclusions about the behavior of this mission mode. The first is that staging the LSAM provides a significant improvement over the single stage option. The LSAM mass devoted to the lunar descent burn is significant due to the relatively high delta-v and payload requirements. By staging the LSAM, the feed back loops of the lunar descent stage dry mass into the ascent and trans-Earth injection calculations can be eliminated. By doing so, the payloads for these burns are significantly reduced leading to a lower initial mass in low Earth orbit requirement. This can be seen in Figure 8. Figure 9 shows a significant sensitivity to the performance of both the descent and ascent stages (represented by the difference between the worst and best performing specific impulses). These results lead to conclusions about which propellants to select for these stages and what penalties can be expected for selecting propellants of lower performance.

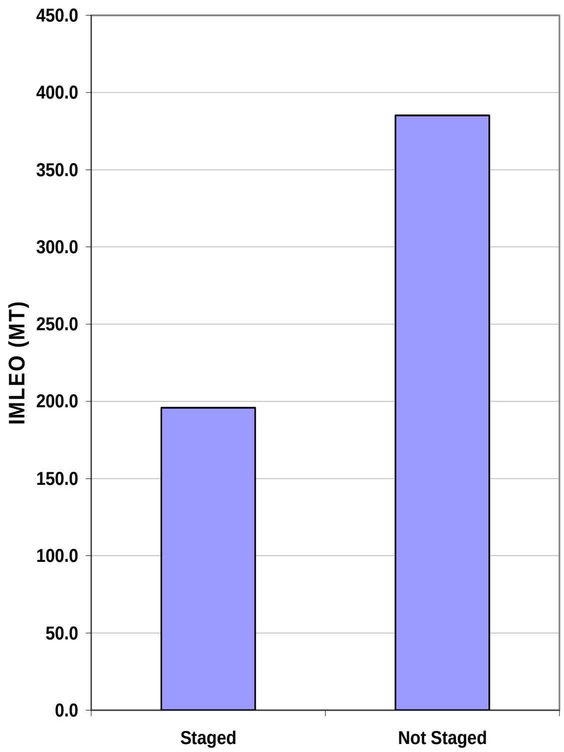

Figure 8. Staged vs. Not Staged LSAM

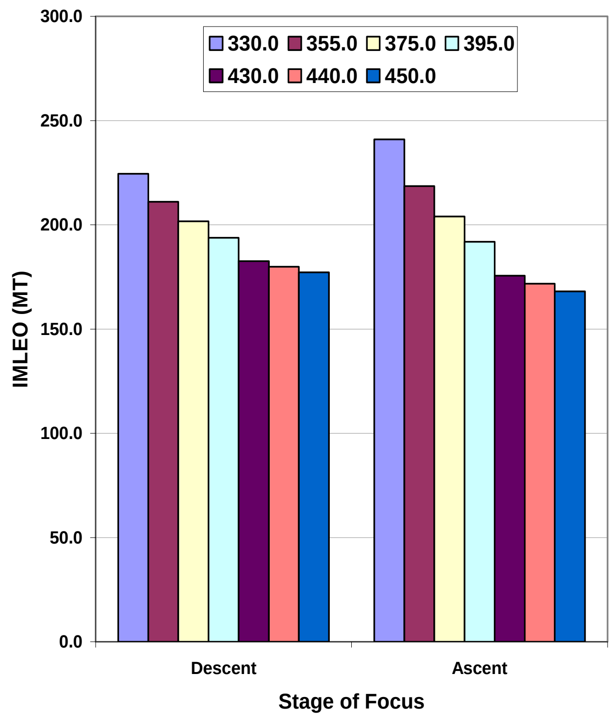

Figure 9. Propellant Sensitivity

3.2. Lunar Orbit Rendezvous: Parking Orbit Trade

In the lunar orbit rendezvous mission mode, the lander system is staged from the trans-Earth injection stage and crew capsule while in orbit around the moon. The crew descends to the surface, performs their surface mission and returns to orbit. There, they rendezvous with the waiting crew capsule and trans-Earth injection stage and return to Earth. This mode was selected for the Apollo missions and, through the use of staging, tends to be a higher performing mode than lunar direct return.

For this analysis, several assumptions were made. Four habitats were employed for the mission that was assessed. A minimal crew capsule was used for crew launch and crew re-entry. A transfer habitat was used to provide the crew with more habitable volume during the transits to and from the moon. Both of these habitats remained in lunar orbit while a combination of surface habitat and ascent habitat descended to the surface with the crew. The surface habitat provided living and work space for the crew during their seven day surface mission and a minimal ascent habitat served to reduce the payload requirement on the ascent stage.

The parking orbit at the moon becomes extremely important to mission planners as mission performance and mission operations complexity are weighed against each other. For this trade, a 100 km circular parking orbit was assessed against a 100 by 5000 km elliptical parking orbit. Due to the requirement to perform maneuvers in lunar orbit to align the return trajectory, elliptical orbits provide a performance benefit by reducing the delta-v requirement for that maneuver. However, this must be traded against the performance penalty associated with descent and ascent from an elliptical orbit. For completeness, these parking orbits were assessed against all possible stage-propellant combinations (243 total combinations). The trade trees and N^2 diagram for this analysis can be seen in Figure 10.

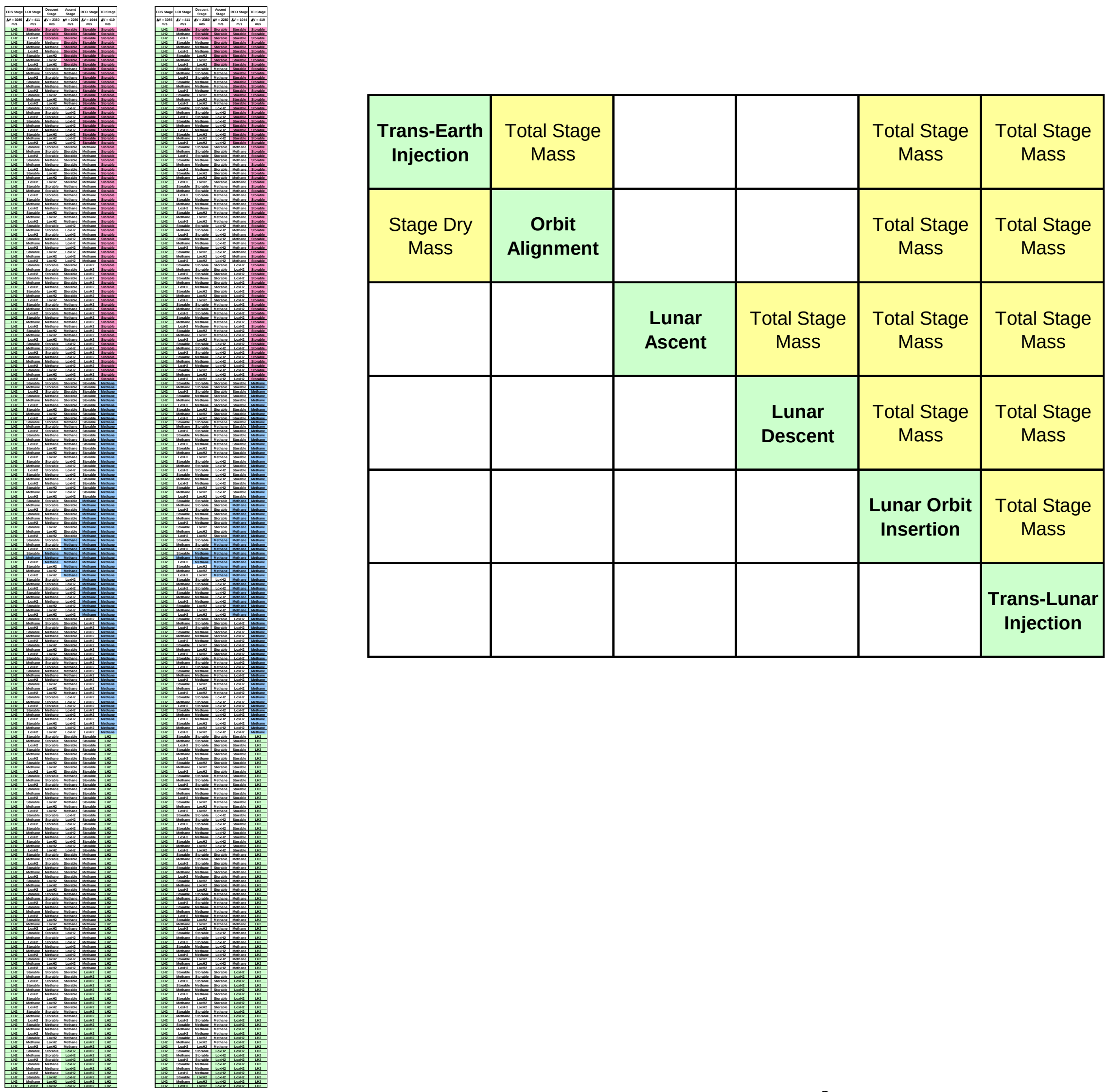

Figure 10. Lunar Orbit Rendezvous Parking Orbit Trade N^2 and Trade Tree

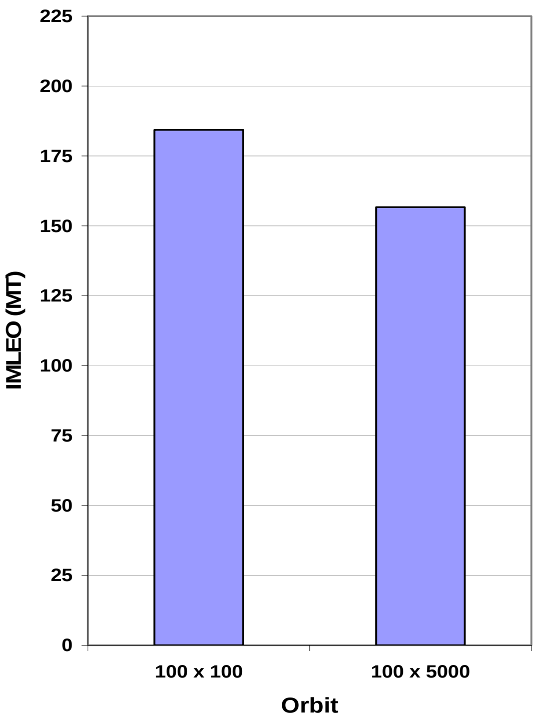

Figure 11. Lunar Parking Orbit Trade

The results of this analysis, displayed in Figure 11, show that the lunar orbit rendezvous mission can benefit from the elliptical orbits. The orbit alignment burn has a significant delta-v requirement in the circular orbit which can be greatly reduced by operating in an elliptical orbit. Also, the lunar orbit insertion delta-v requirement is reduced which shows significant benefits to the lunar orbit insertion stage. From the N^2 diagram, it should be noted that this lunar orbit insertion stage carries significant payload mass and a reduction in the delta-v requirement will have significant impact.

3.3. Lunar Orbit Rendezvous: Propellant Combination Trade

The characteristics of the lunar orbit rendezvous mission mode are unchanged from the previous example. In this trade, a lunar parking orbit of 100 km circular has been selected. Habitat mass assumptions and staging schemes are also unchanged. In this trade, an assessment of mission performance trends based on propellant combinations is performed.

With the exception of the Earth departure stage which is assumed to always use a Lox/LH_2 propellant, each stage is assessed using Lox/LH_2, Lox/CH_4 and NTO/N_2H_4. All possible combinations of stage propellant selections are assessed resulting in 243 possible mission configurations. The trade tree and N^2 diagram found in Figure 10 also apply to this trade analysis. Once the data is provided, average initial mass in low Earth orbit (IMLEO) values are computed for each stage-propellant combination. As in the lunar direct return propellant trade, the gap between the highest and lowest average IMLEO values for each stage indicate the level to which the mission is sensitive to the propellant selection of that stage.

The results, shown in Figure 12, reveal several drivers of mission performance. The lunar orbit insertion stage shows the greatest gap in average IMLEO between the three propellant combinations. This would indicate that selection of a propellant combination for this stage is extremely important. As was mentioned in the previous section, this stage shows a significant payload burden from the N^2 diagram. This is most likely the factor that leads this stage to be such a significant performance driver.

Likewise, the descent and orbit alignment (REO) stage are significant performance drivers. The descent stage represents a combination of high payload mass and high delta-v requirement. The orbit alignment stage has a significant delta-v requirement due to the selection of a low, circular parking orbit. Propellant selection for these stages is important, but probably not as important as the lunar orbit insertion stage.

Ascent and trans-Earth injection stages appear to be the least significant mission performance drivers. These stages represent low to moderate delta-v requirements with very low payload masses. The selection of propellant for these stages is not critical and may be driven by mission safety considerations (the selection of lower performing hypergolic propellants for higher mission reliability) without a high level of concern for overall mission performance.

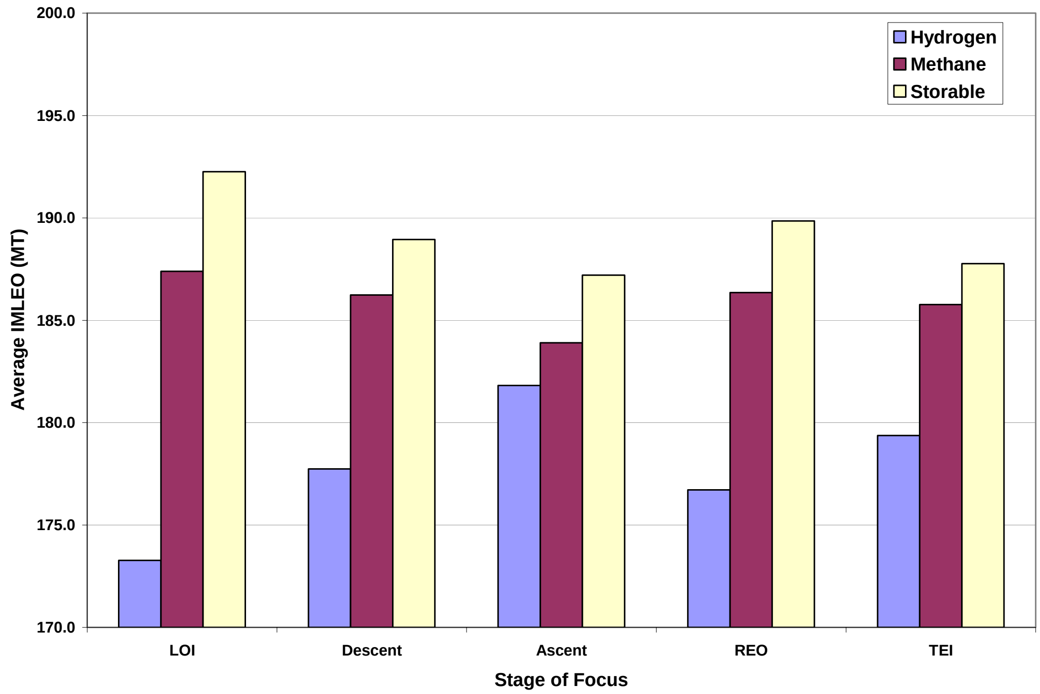

Figure 12. Lunar Orbit Rendezvous Stage Propellant Trade Results

4.0 Summary

While the systems engineering process as a whole is not specifically tailored for conceptual, high level analyses, several of the tools within that process prove useful when performing complex mission architecture performance assessments. The N^2 diagrams and trade trees provide the organization and structure to help identify the interdependencies that exist between system elements and the decisions that must be made in developing the best performing system. Coupled with simple, Excel-based models broad trade trees can be analyzed to provide reasonably accurate data for the purpose of isolating performance trends and drivers and help steer the more detailed analyses in the most promising directions. The assessment of the trade space that covers all possible lunar mission architectures is a complex task, but through the use of these systems engineering tools, engineers are beginning to see the probable answers materialize, taking us one step closer to returning to the moon.

5.0 Acknowledgements

The work presented in this paper was completed as part of a series of quick analyses under the direction of the Space Transportation Programs & Projects Office at the Marshall Space Flight Center in Huntsville, Alabama. In particular, the author would like to thank Hank Kirchmyer and Ron Thomas for their help and direction during the course of these analyses, especially for their work on the trade trees presented and their continued direction of these and similar studies in support of NASA's effort to return humans to the surface of the moon.

6.0 References

[1]ESMD-RQ-0006,. “Lunar Architecture Broad Trade Study Final Report”, Version Baseline, 1 September, 2004

[2]Stevens, K. et. al., “Lunar Engine Comparison Study” NASA TM. In Press.

[3]Percy, T & Benfield, M. “Manned Lunar Missions: An Exercise in Propulsion Trades & Sensitivities”, AIAA-2005-4008, Joint Propulsion Conference, 2005.